# A Novel FM Microwave Fiber-Optic Link for Antenna Remoting and Phased Arrays

Final Report

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## Abstract

*In this final report, we report the first analysis and experimental demonstration of tunable microwave/millimeter wave signal generation in two-section gain-coupled DFB lasers. Continuous tuning from 20 to 64 GHz was directly observed and characterized both in the electrical and optical domain. The mechanism of microwave generation in two-section gain-coupled DFB lasers is different from that of two-section index–coupled DFB lasers previously reported. As a result, gain coupling can lead to simultaneous large modulation indexes and high frequencies in two-section DFB lasers.*

Optical generation of microwave/millimeter-wave signals has potential applications in optical subcarrier multiplexing [1,2], photonic link signal mixing [3,4], all-optical clock recovery [5] and generation of high-bit rate soliton-like sources [6-8]. The highest frequency so far was generated in two-section strongly index-coupled ($\kappa = 300\,cm^{-1}$) DFB lasers [9]. It is believed that the mechanism for the generation of microwave signals is due to nonlinear mode beating through nonlinear interactions of the exchanged photons with the carriers in the active media of both sections [10]. The modulation index of these microwave signals is expected to be rather low because of the small overlap of the modes. The stronger the DFB grating (i.e., the larger the value of $\kappa$) the smaller the modulation index [10]. Therefore, it would be difficult to experimentally generate microwave signals with large modulation index in two-section index-coupled DFB lasers. We report in this letter the generation of microwave signals in two-section gain-coupled DFB lasers. Our simulation indicates that the nonlinear mode-beating mechanism of microwave generation in two-section gain-coupled DFB lasers is different from that of two-section index–coupled DFB lasers previously reported. Furthermore, gain coupling can lead to simultaneous large modulation indexes and high frequencies for two-section DFB lasers. We

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also report the first experimental generation of continuously tunable microwave signals from (20-64) GHz in two-section gain-coupled DFB lasers.

| Parameter | Value |
|---|---|
| Injection Current in Section 1 | $88\,mA$ |
| Injection Current in Section 2 | $62\,mA$ |
| Central Wavelength | $1.55\,\mu m$ |
| Differential Gain Coefficient | $1.6 \times 10^{-16}\,cm$ |
| Length of Each Section $l_a = l_b$ | $300\,\mu m$ |
| Optical Loss Coefficient | $40\,cm^{-1}$ |
| Effective Group Index | $3.7$ |
| Carrier Density at Transparency | $2.1 \times 10^{18}\,cm^{-3}$ |
| Facet Reflectivity | $10^{-6}$ |
| Effective Modal Index | $3.5$ |
| Carrier Life Time | $1.25\,ns$ |
| Static Bragg Detuning $(\delta = (\pi/n_2\Lambda_2 - \pi/n_1\Lambda_1))$ | $56\,cm^{-1}$ |

Table I: Values of the parameters of the device used in the simulations

The dynamics, including the generation of microwave signals, of the two-section index-coupled DFB lasers was investigated in [10] using a mode-expansion approach. For the results presented here, we have employed a spatiotemporal large-signal simulation using a traveling-wave model [11]. In this approach, the partial differential equations governing the dynamics of multi-section DFB lasers is solved by choosing the ratio of the spatial and temporal integrating step sizes to be exactly the group velocity. In so doing, the integration of the dynamics becomes explicit; the state variables only depend numerically on the state variables in previous steps. The parameters of the devices are shown in Table I. The static detuning ($\delta = 56\,cm^{-1}$), primarily due to current induced heating, is essential for the generation of high-frequency microwave signals from mode beating [10]. Figure 1 is a comparison of the dynamics of an index-coupled ($\kappa = 100\,cm^{-1}$) and a gain-coupled ($\kappa = 99.05 + i9.95\ cm^{-1}$) DFB laser with otherwise the same

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parameter set including the magnitude of the coupling constant $|\kappa| = 100\,cm^{-1}$. The modulation

index for the gain-coupled laser is almost 100%, while that for the index-coupled laser is only
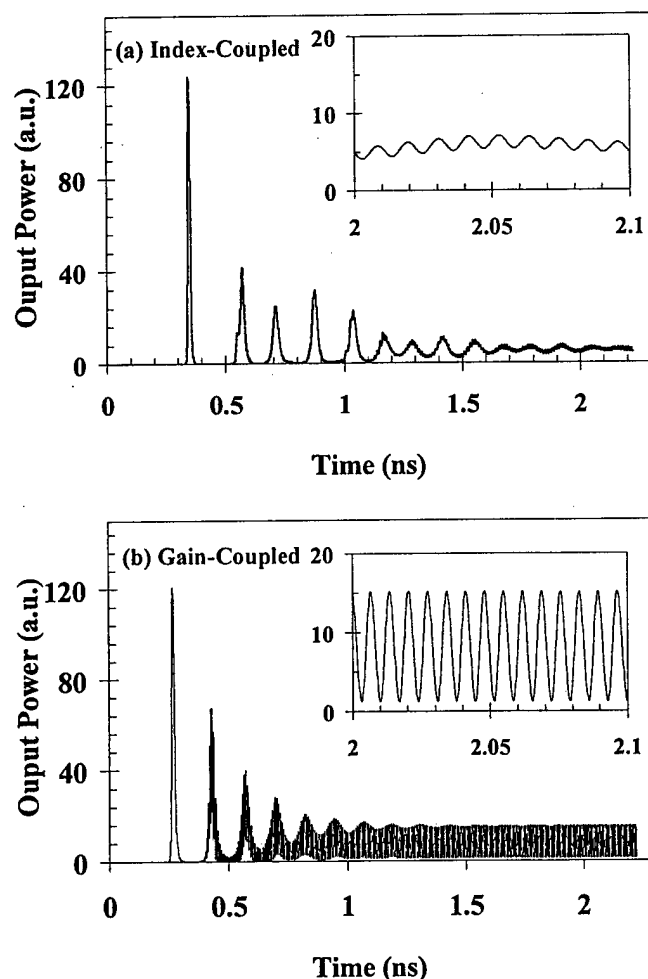
about 10%.



Figure 1  Dynamics of the two-section index (upper) and gain-coupled (lower)
DFB lasers with parameter values shown in Table 1.

The difference in the dynamic behavior of the index- and gain-coupled two-section DFB lasers

can be understood by examining and comparing the reflectivity spectra of the two sections for

the index- and gain-coupled devices, as shown in Fig 2.  The reflectivity spectra were computed

using the same parameters as used for Fig. 1, with the average gains of the two sections adjusted

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based on the injection currents. As indicated in [10], the two modes, A and B, indicated by the arrows in Fig 2 (a), responsible for the microwave generation in the index-coupled two-section DFB lasers belong primarily to their respective sections. Each mode lies in the stop band of the other section. Since mode A is almost completely reflected back into section A from section B and vice versa, the modulation indexes of the beat signal at the output facets are expect to be low. The only exception is when mode A and B are sufficiently close (low frequency microwave signal) so that mode A approximately satisfies the phase condition for section B and thus can propagate into section B, and vice versa. For the gain-coupled two-section DFB on the other hand, one mode, B, primarily belongs to the particular section B and lies in the stop band of section A. The second mode A is not in the stop band but instead coincides with a Fabry-Perot mode of section B. As a result, mode A can propagate into and be amplified by section B. This can occur at relatively large mode separations (or high microwave frequencies). This is why two-section gain-coupled DFB lasers can achieve high frequencies and large modulation indexes simultaneously, as shown in Fig. 1.

It should be pointed out that the mechanisms for the generation of millimeter wave intensity modulation presented here for the two-section index-and gain-coupled DFB lasers are different from that of the four-section index-coupled DFB laser by Lima *et al.* [12]. In [12], the intensity modulation is due to simultaneous oscillation of two degenerate modes of the same DFB structure on either side of the stop band, for example, mode B and mode C in Fig. 2(a). The modulation frequency is determined by the width of the stop band, which is approximately $\kappa L$. High modulation index is expected because these two modes are degenerate. Four sections are needed to ensure simultaneous and stable lasing of the two degenerate modes rather than hopping between the two degenerate modes.
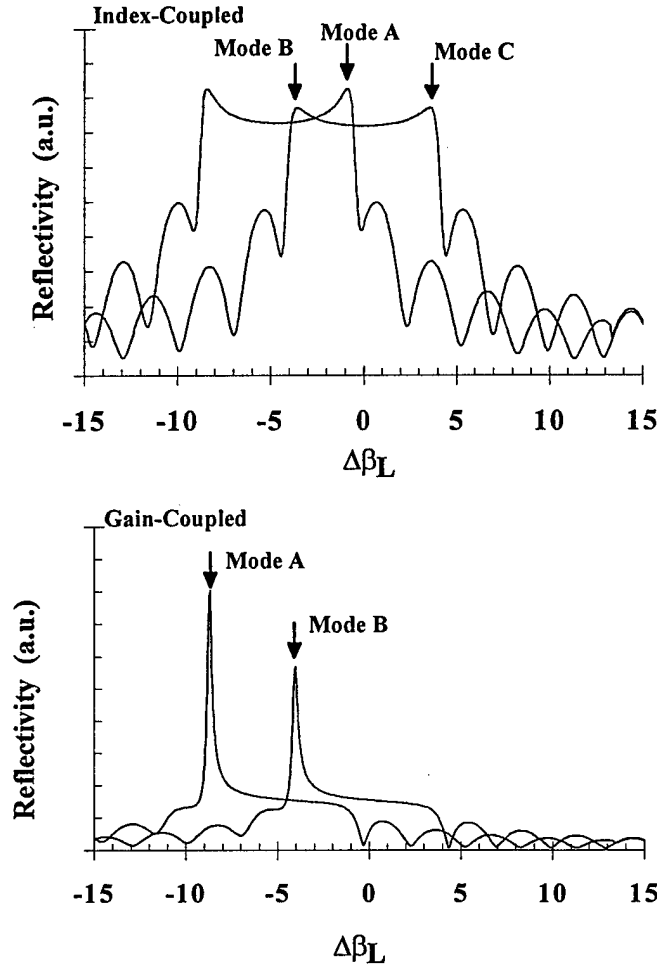
Figure 2  Reflectivity spectra of individual sections of the two-section index (upper) and gain-coupled (lower) DFB lasers with parameter values shown in Table 1.  Arrows indicate the modes responsible for the generation of the microwave/millimeter wave signals.

Now we proceed to describing the experimental results.  The two-section gain-coupled

DFB lasers used were multi-quantum-well devices [13,14].  The lengths of the two sections are

approximately $275\,\mu m$ each.  The coupling constant for each section is estimated at $|\kappa|L=3$ with

about 10 % gain coupling.  The two-section laser was temperature stabilized at $17^{\circ}C$.  When

operated individually, the threshold current for each section is around $12\,mA$.  The output of the

laser was coupled into a single-mode fiber for the monitoring of the optical spectrum of the laser

(using an HP 70951B) and the RF spectrum of the microwave intensity modulations on the

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optical carrier (using an HP 8565 E). The photodetector used has a 3-dB bandwidth of 25 GHz (New Focus 1434) followed by a 25-GHz amplifier (Miteq AFS42-0100-2500-60-8P-42). For over 50 GHz, the microwave intensity oscillations were down converted all-optically [4]. The output of the laser was coupled into a 12-GHz integrated Mach-Zehnder intensity modulator (UTP MZM-150-120-T-1) biased at $v_\pi$ and overdriven by a 10 GHz signal of about 25 dBm. The resultant second harmonic at 20 GHz converted the incoming microwave intensity oscillations above 50 GHz down by 20 GHz so that the down-converted signals fell within the bandwidth of the RF spectrum analyzer.
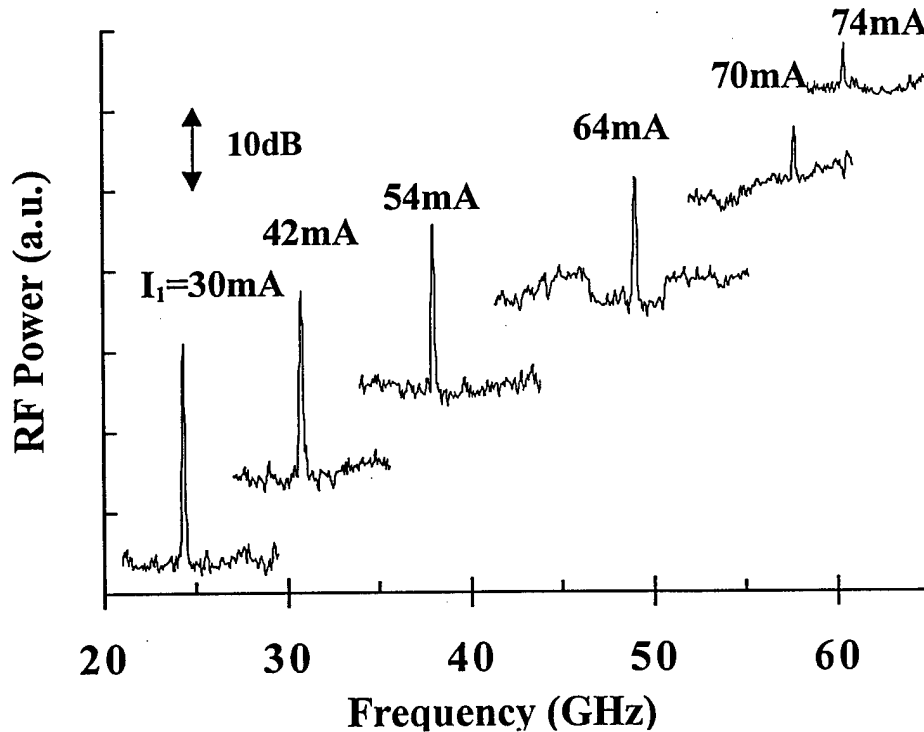


Figure 3 The RF spectra of the continuously tunable microwave/millimeter signals from 24 to 62 GHz on the optical carrier.

Figure 3 shows the continuous tuning of the microwave signal from 24 GHz to 62 GHz as the bias current for one section is tuned from $30\,mA$ to $74\,mA$ while that for the other section is fixed at $25\,mA$. The decrease in the detected microwave power at high frequency is partially due

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to the frequency response of the photodetector, which has a 3-dB bandwidth of 25 GHz. Figure 4 is the corresponding optical spectra. The mode separation corresponds well with the observed microwave frequency. The 3-dB linewdith of the detected microwave/millimeter wave signals is 2.5 MHz with a long-term drift of about 20 MHz. This is much better than the free-running device in [12] that had a 3-dB linewidth of about 120 MHz, a long-term drift of 150 MHz and a tuning range of less than 20 GHz (adjustment of multiple bias currents required) [15]. The modulation index of the microwave signals at 24 GHz is estimated at about 90%. This is based on the fact that the measured peak power spectral density of the microwave signal is $-50\,dBm\,/\,MHz$, the photodetector has a responsivity of $0.2\,A\,/\,W$, and a load resistance of $50\,\Omega$. Taking into account of the amplifier gain of $28\,dB$, this leads to a peak optical power fluctuation of $0.199\,mW$ ($0.398\,mW$ peak-to-peak) whereas the average optical power was measured at $0.215\,mW$. As commented earlier, these signals can be used to generate high-bit rate soliton-like source for optical time-division multiplexing (OTDM) applications. The use of these devices in combination with dispersion-tailored fiber to form OTDM sources and the characterization of the resultant pulses in the optical domain have been reported in [8].
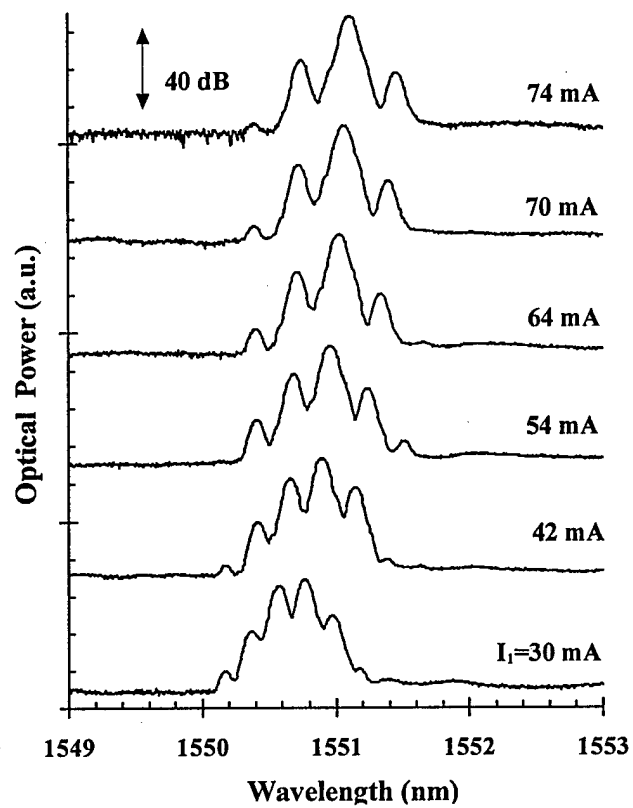
Figure 4. The optical spectra corresponding to Fig. 3.

In conclusion we demonstrated, for the first time, the generation of tunable microwave/millimeter wave signals in two-section gain-coupled DFB lasers. Continuous tuning from 20 to 64 GHz was achieved. Characterization in the electrical domain of the tunable millimeter-wave signals is important for applications in fiber radio. Spatiotemporal dynamic simulation of the two-section gained- and index-coupled DFB lasers reveals that the gain coupling can lead to large modulation indexes and high frequencies simultaneously. The dynamic simulation also indicates that the underlying physical mechanism responsible for large modulation index is due to enhanced transmission characteristics associated with the gain grating and will be reported in details elsewhere. Optical generation of microwave/millimeter-wave signals reported here can find potential applications in optical subcarrier multiplexing, photonic link signal mixing, all-optical clock recovery and generation of high-bit rate soliton-like sources.

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